The Flowing Liquid Retention Experiment (FLIRE)

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Outline

- Brief introduction
- Analysis procedure
- Retention results
- Model for estimation of diffusion coefficient
- Bubble formation?
- Future work

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Flowing Liquid Retention Experiment (FLIRE)

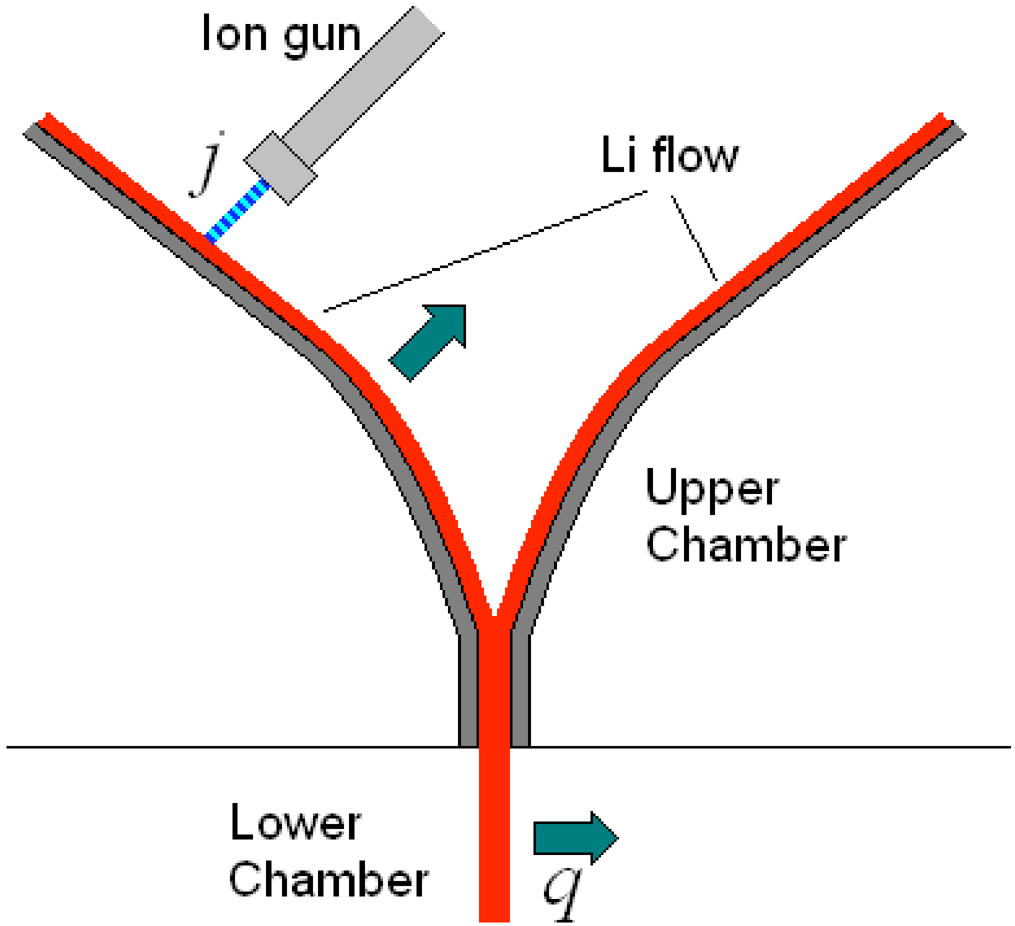
- Designed to study the interaction between flowing liquid surfaces and plasmas
- The heart of FLIRE are the two vacuum chambers, connected by a small opening
- In one of them (upper) the metal is exposed to the plasma
- In the other (lower) desorption from the metal is measured
- During flow, chambers are isolated from each other
- Only particles carried by the metal are detected

Retention measurement in FLIRE

- A direct measurement is the retention coefficient:

q: release rate in the lower chamber

j: injection rate in the upper chamber



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Pumping speed measurement

- Small amount of He (10^{-7} - 10^{-8} Torr) is bled into the chamber
- Wait until equilibrium is established (P_0)
- Stop the He leak suddenly
- Record data of P vs t until background is reached (P_{bckg})
- Exponential curve is obtained
- Fit to the following model:

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Adjusted Pressure

- Pressure diagnostics usually calibrated for nitrogen
  - Factor of 5 correction for measuring helium instead of nitrogen due to much higher ionization potential
- Pressure is measured near room temperature, but helium is release at liquid lithium temperature
  - Factor of 2 correction for temperature difference between lithium and pressure gauge.
- All data shown is corrected “pressure” equivalent to density at
  - $P_{adjusted}$=10 $P_{measured.}$

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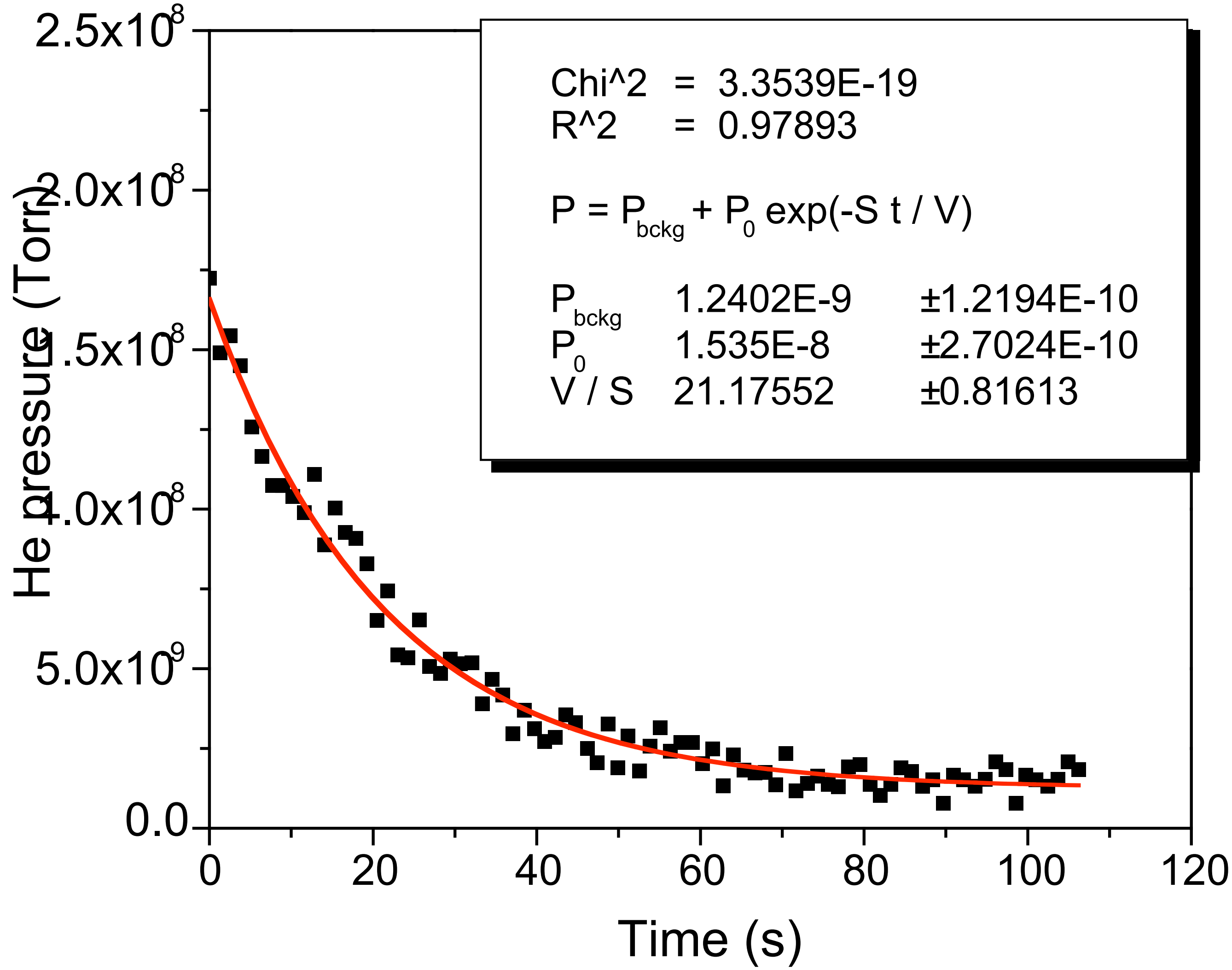

$$S = 0.33 \pm 0.02 \text{ l/s}$$

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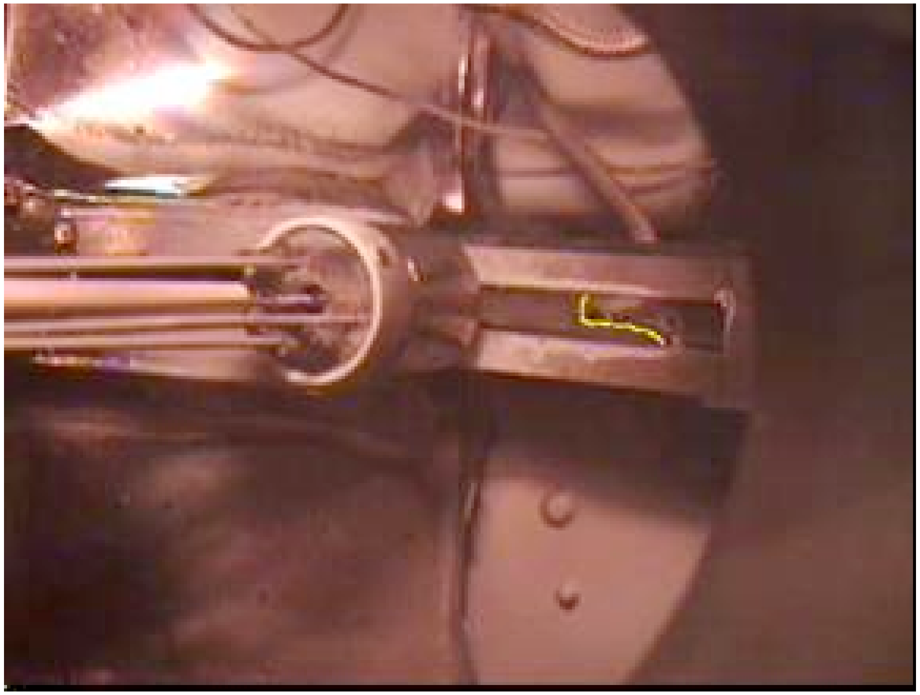
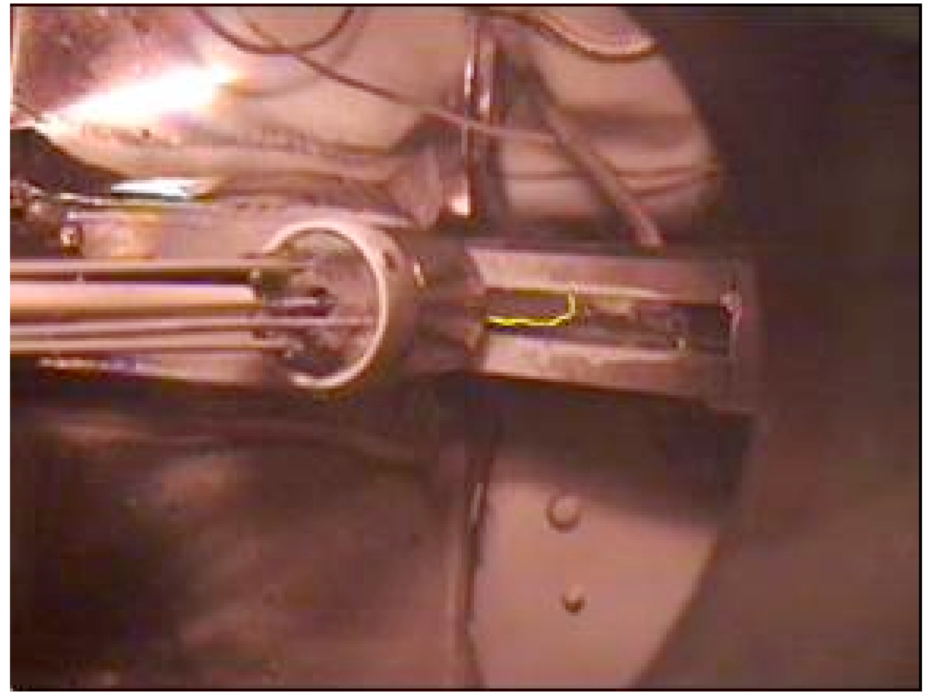
Flow velocity calculations

- Two approaches:
  - Flow video capture
  - Tank discharge analysis
- Video capture not very reliable
- Tank discharge analysis gives more accurate results
- The two methods give consistent results

Velocity calculation from video





$v \sim 25 - 50$ cm/s

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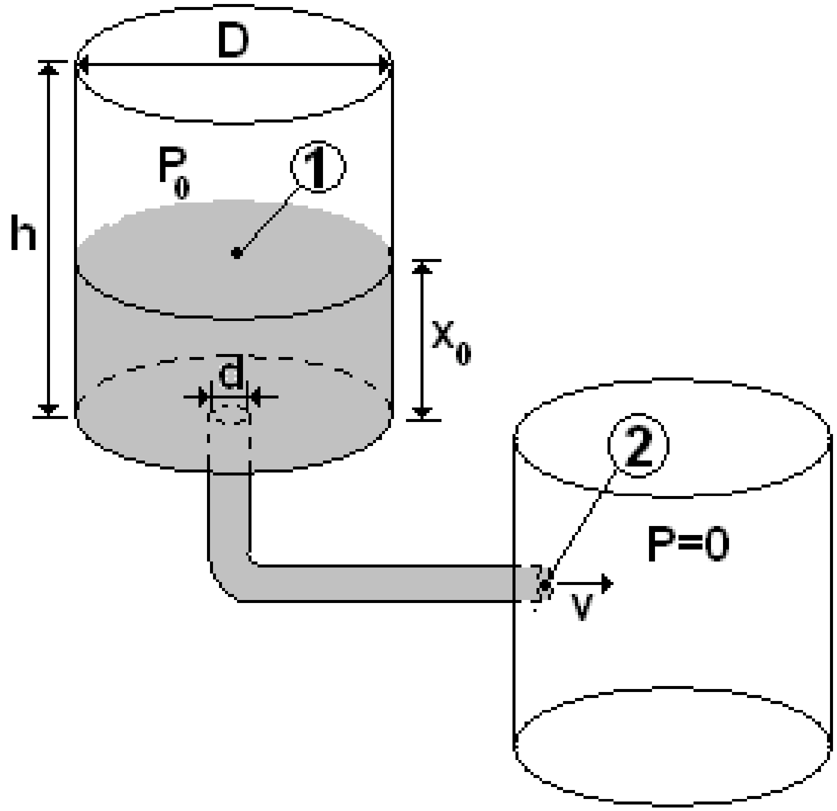
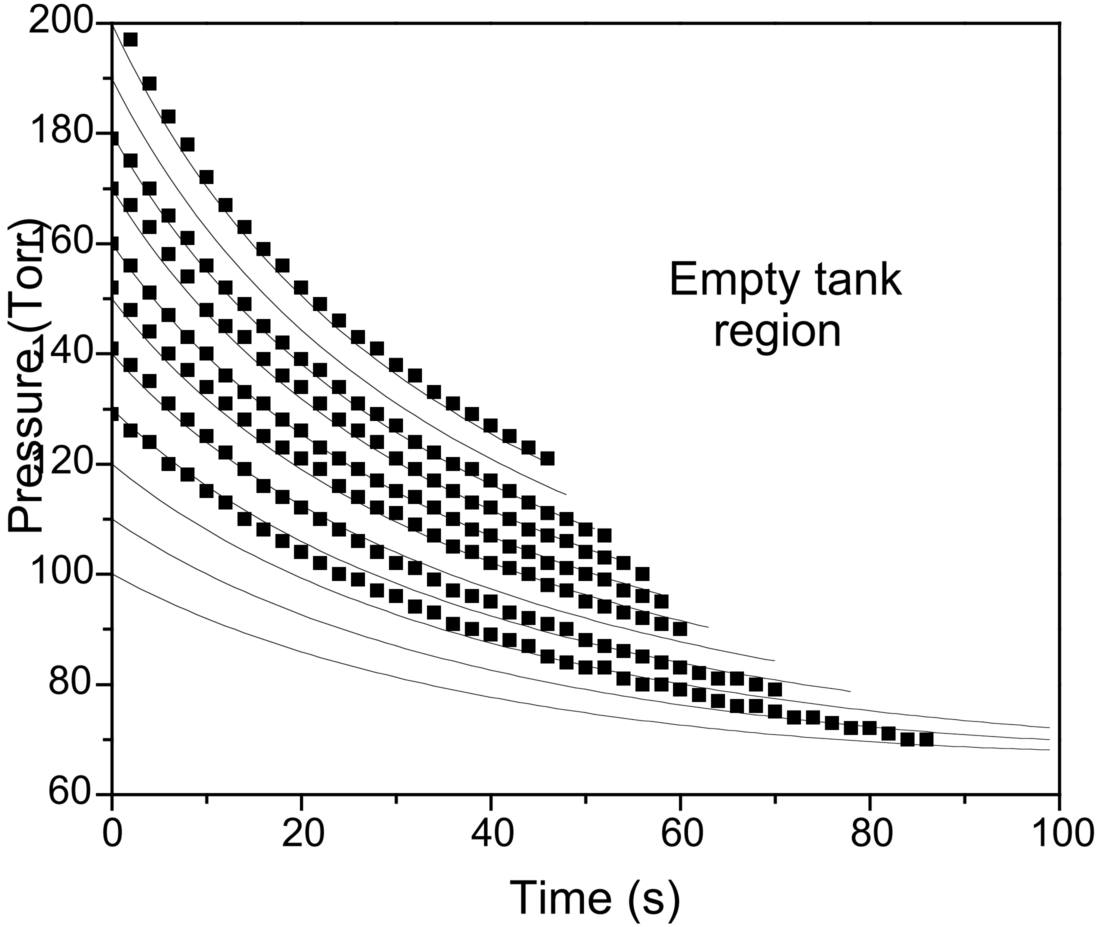
Tank discharge model

- Supply tank at initial pressure P_0
- Discharging into an empty tank ($P=0$)
- Initial level x_0
- Cylindrical supply tank height h and diameter D
- Exit pipe diameter d

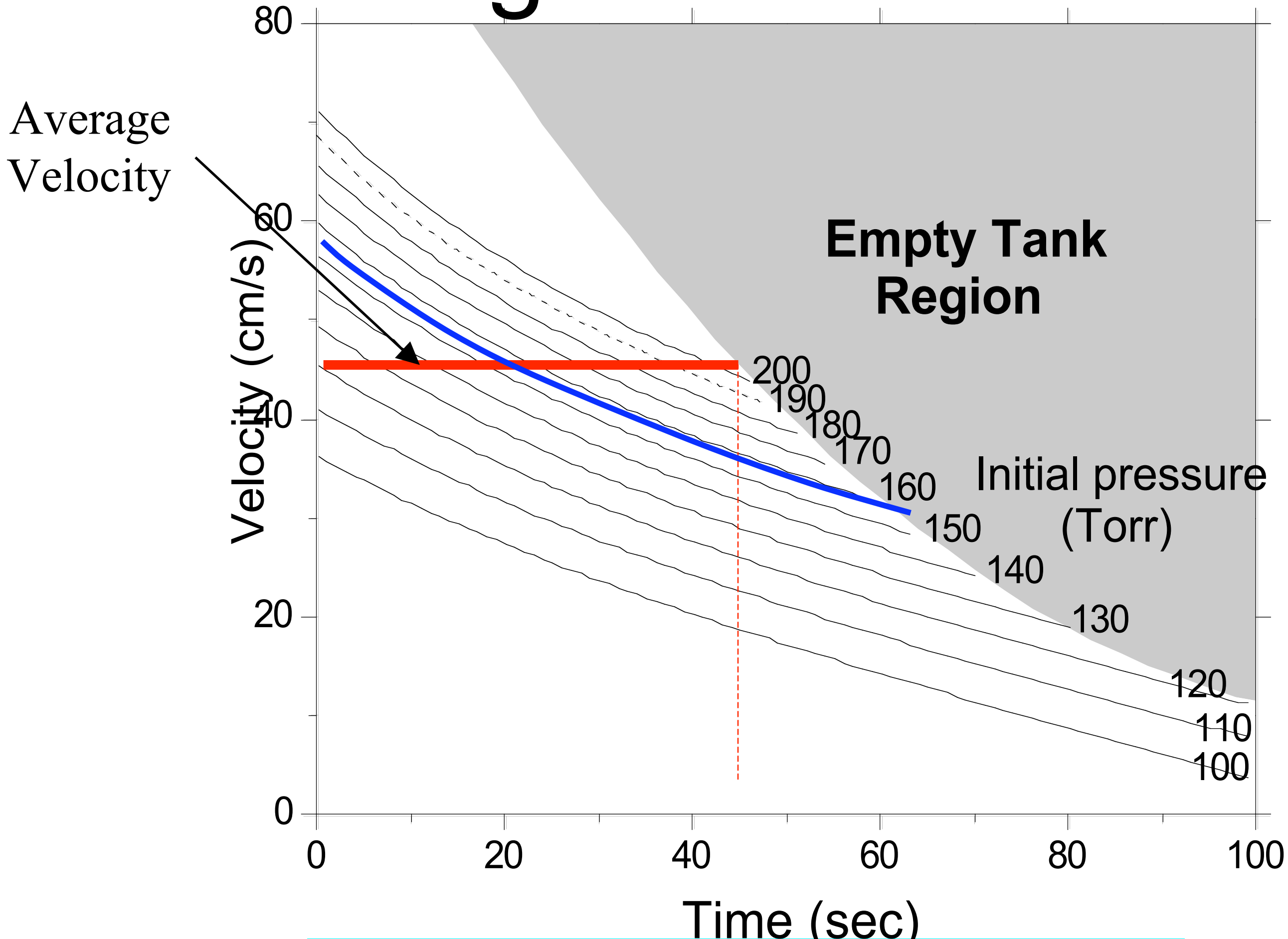


Model benchmark



- Dots are experimental data for tank discharge
- Lines represent the model described
- Perfect match for high pressures
- Deviation observed close to the end of the runs as pressure goes down

Velocitv @ 150 Torr driving pressure 'ng first 45 seconds



$v = 44 \pm 6$ cm/s

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Comparison with video estimate

- Video gives 25 – 50 cm/s for initial driving pressure of 140 Torr
- Model gives 44 cm/s
- When using two ramps, divide the result of the model by two since it is based on total mass flow and the same total time is taken to move the same volume from the reservoir.
- Model reproduces experimental tank discharge data and is of same order as independent measurement

Experiments performed

- Helium
  - Beam energy varied between 0.5 and 4 keV
  - Two sets with two different ion currents
  - All other parameters constant

  - Another two sets, energy varied between 0.5 and 4 keV
  - Velocity doubled for one of the runs (single-channel flow)
  - All other parameters constant

Helium experiments

PARAMETER	SET A	SET B
Li temperature (°C)	230±10	230±10
Li flow velocity (cm/s)	44±6	44±6
Beam energy (keV)	0.5-4	0.5-4
Beam current (μA)	1.2 (max)	1.8 (max)
Pumping speed (cm^3/s)	420±60	330±20
Path length before exit (cm)	10.5±0.5	10.5±0.5
Run duration (s)	45	45
Chamber volume (cm^3)	7000±250	7000±250

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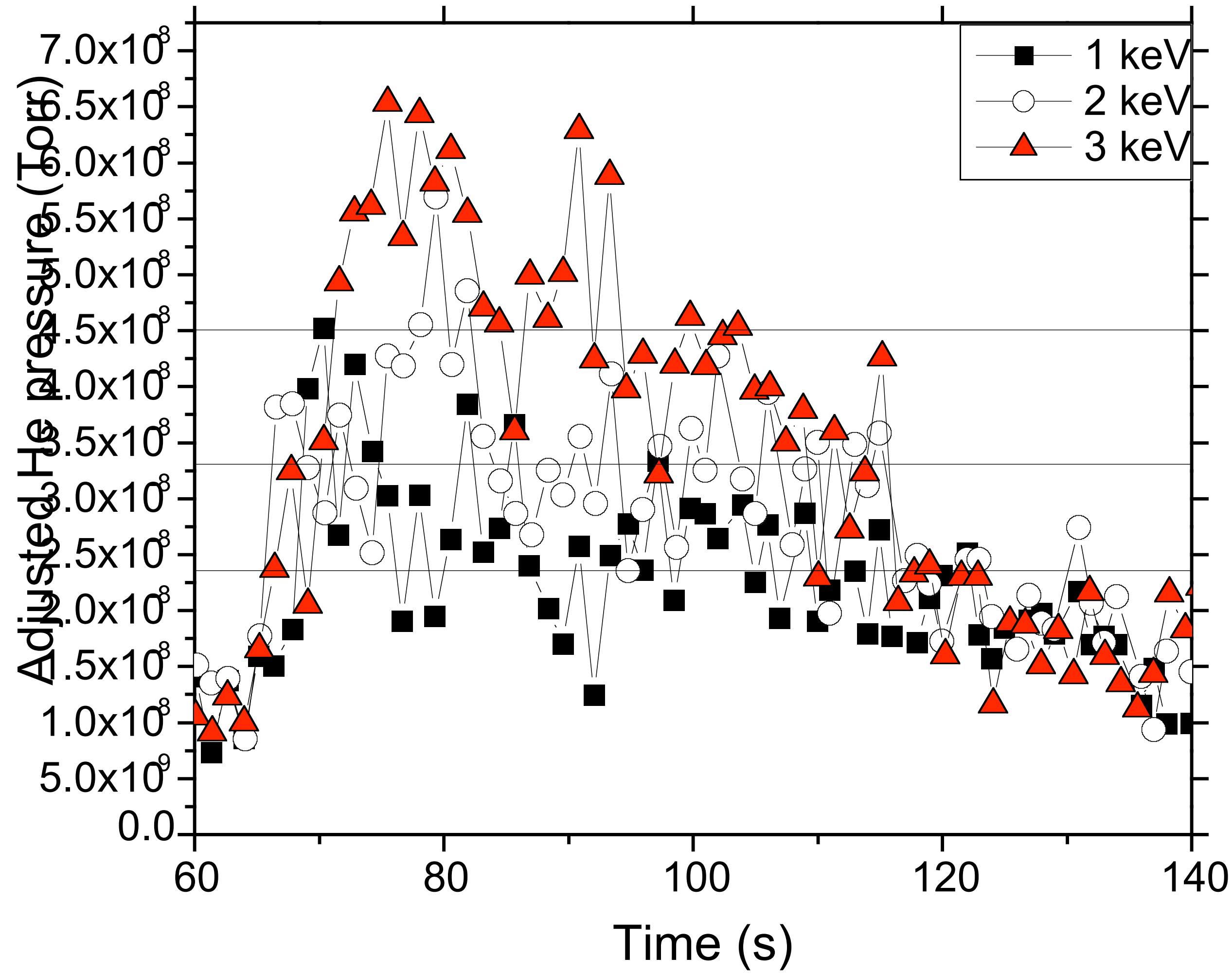
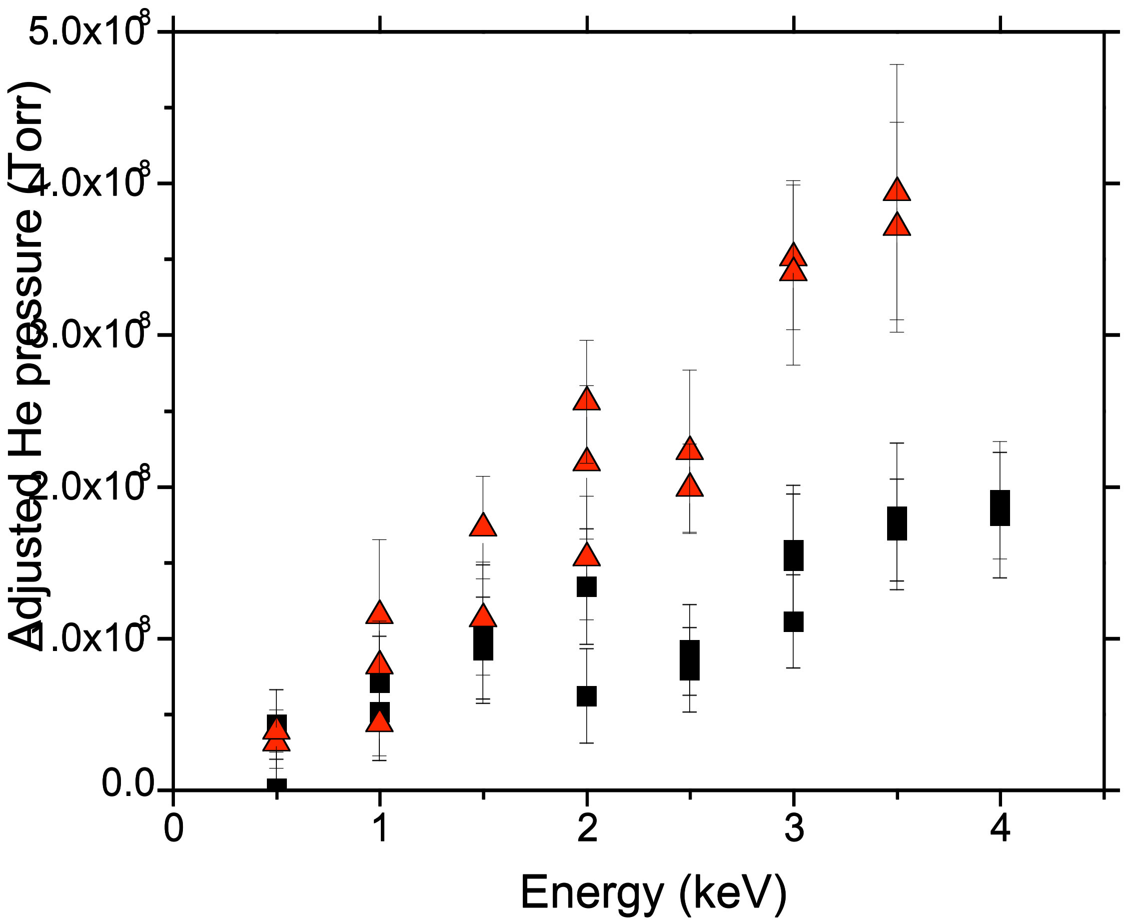
Pressure traces, high current set



Summary, P_{avg} vs E



- Data for low current set…
- …and high current set
- Two different slopes
- Higher current, higher slope
- Different pumping speed.

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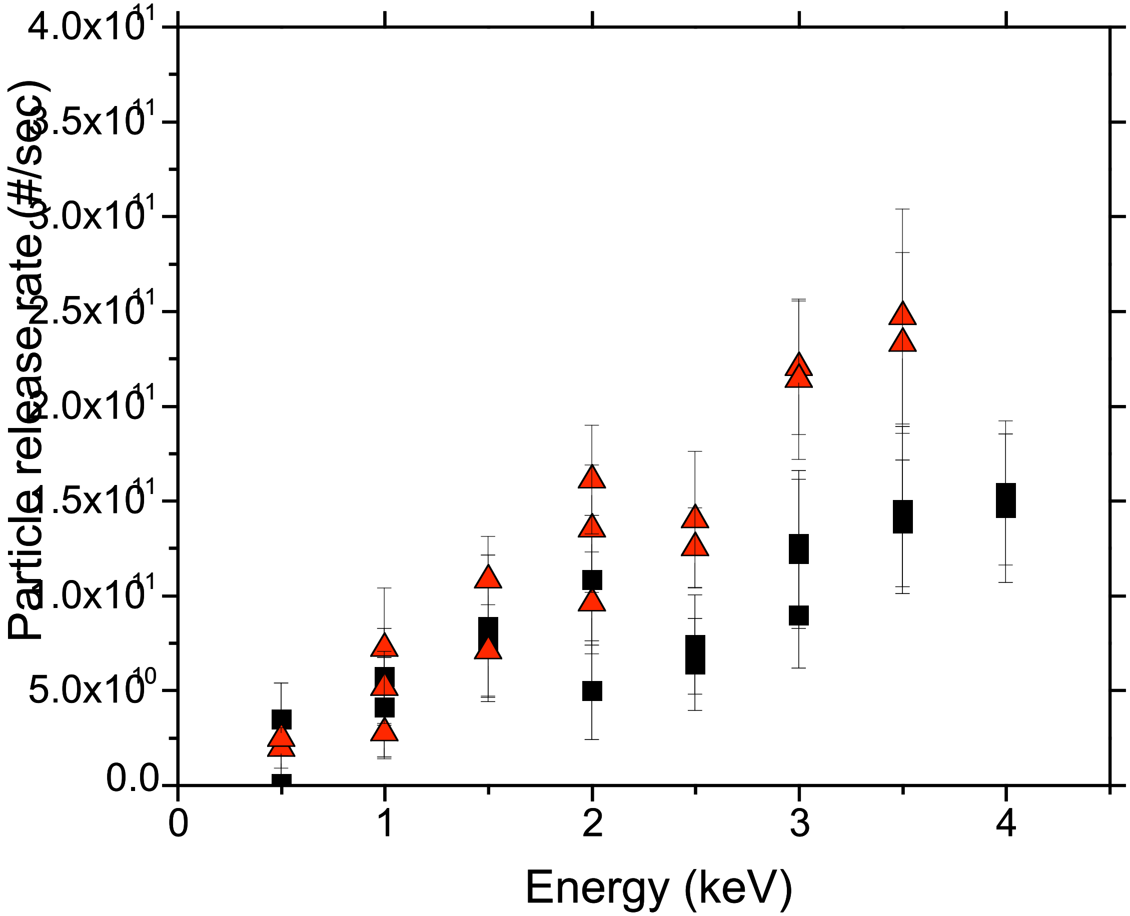
Summary, q vs E



- Data for low current set…
- …and high current set
- Two different slopes
- Again, higher current, higher slope
- Pumping speed accounted for

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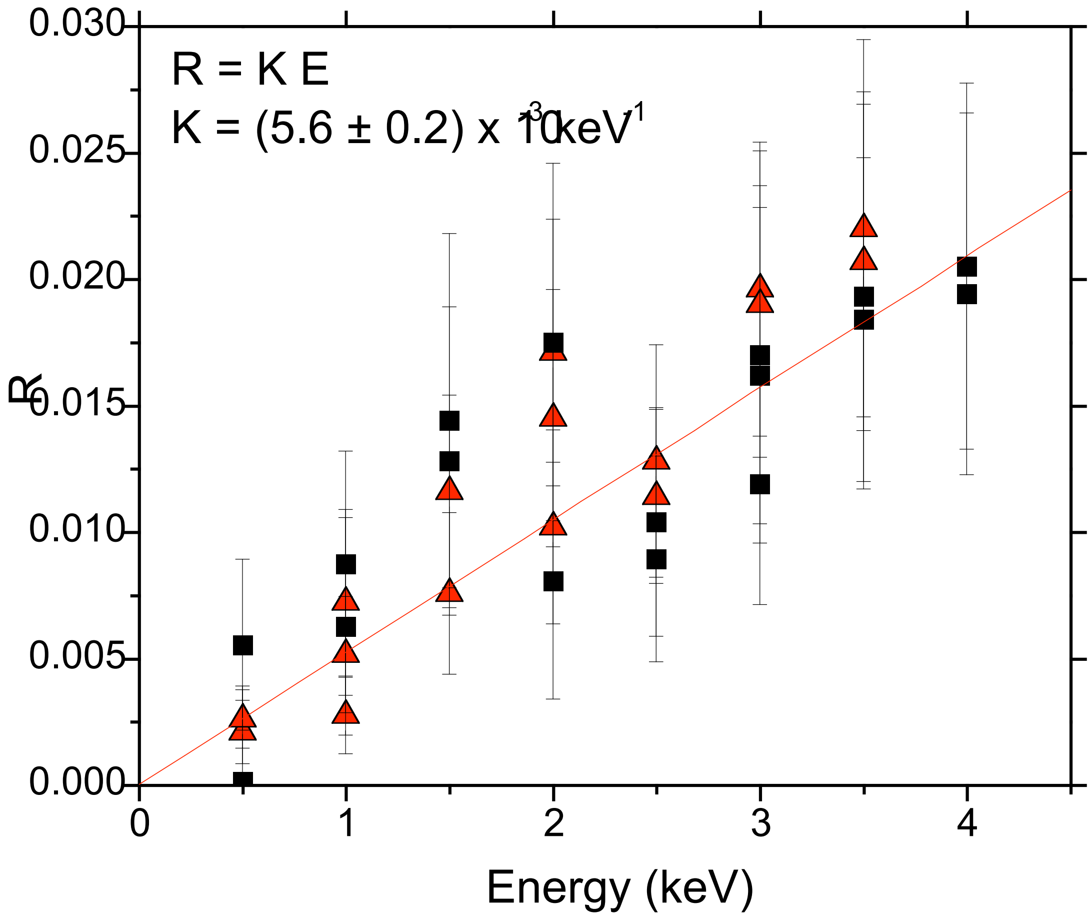
Retention results



- Data for low current set…
- …high current set
- Difference in slope non-existant
- Retention independent of current as it should be

Effect of velocity

- Switching from single to double flow allows to change the velocity by a factor of 2 without increasing the mass flow rate
- No risk of pool formation by velocity increase
- Two sets were taken as a function of energy, one with single flow and one with double flow. All other parameters constant
- Data taken with the cryopump, so reliable pumping speed value was not available
- Therefore a diffusion coefficient can not be estimated, but dependence of R with v can be checked

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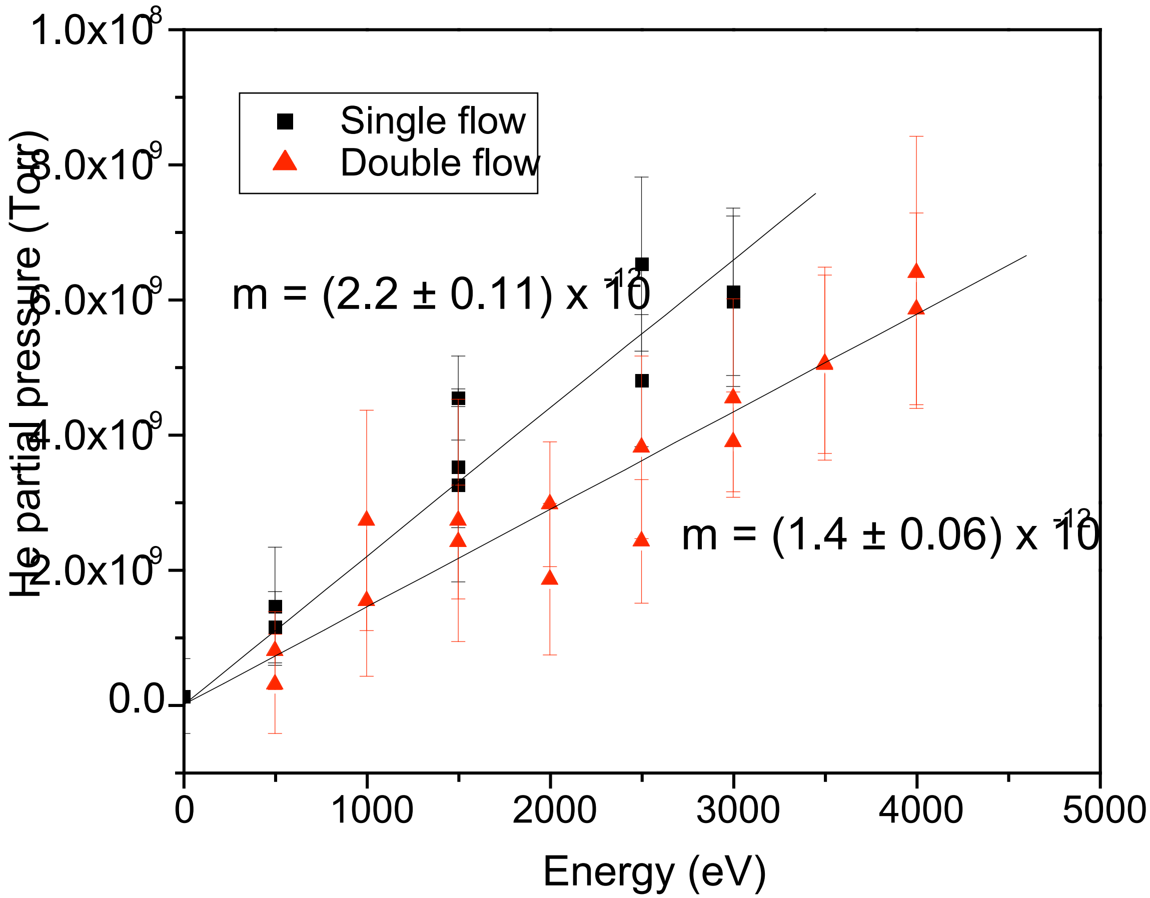
Effect of velocity on R



- Again, R is linear with energy
- Difference in slope due only to flow velocity
- Ratio of slopes (~1.5) close to the square root of 2 (~1.41) as expected.

Diffusion calculations

- Two approaches:
  - Using the linear interpolation
  - Point-by-point calculation

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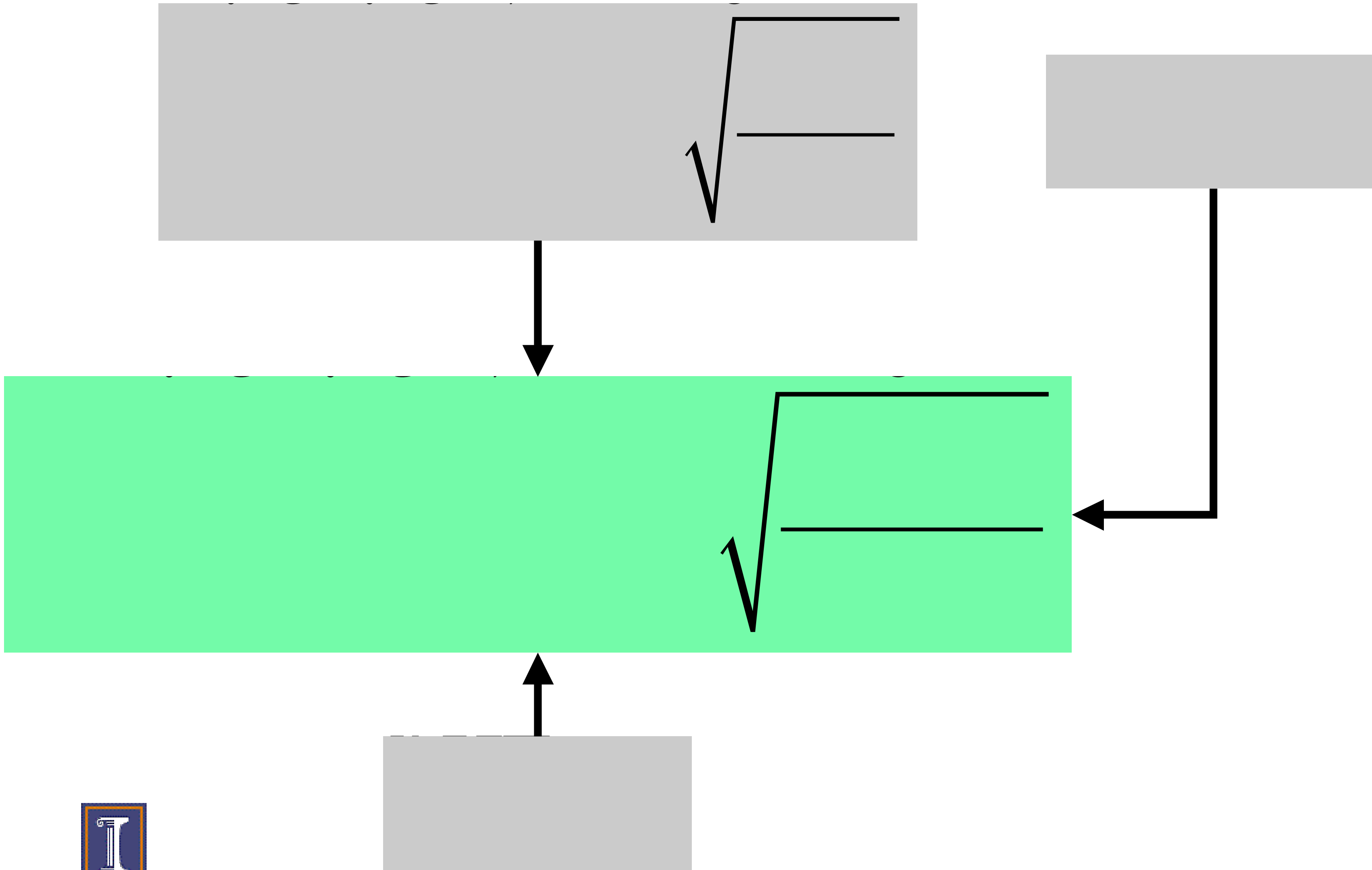
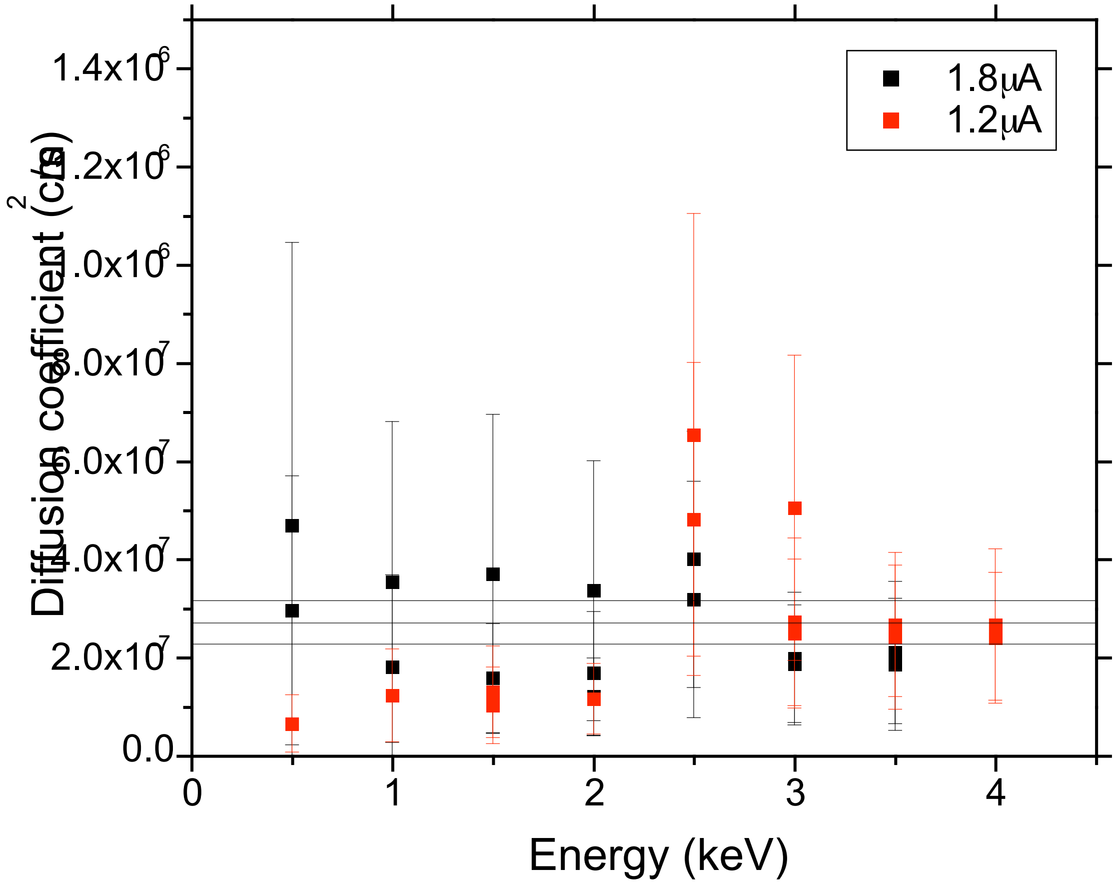
Using linear interpolation



Diffusion value from linear interpolation of *R*

$D = (2.3 \pm 0.4) \times 10^{-7}\ \mathrm{cm^2/s}$

Individual D calculations



$D_{avg} = (2.7 \pm 0.4)$ x 10^{-7} cm^2/s

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Why is the effective diffusion coefficent so low? Long term He retention

- How accurate is to assume that all the helium comes out?
- What if He content is too small to come out by pure diffusion?
- What if bubbles are formed which would diffuse more slowly?
- Thermal annealing of the lithium after exposure may shine some light…

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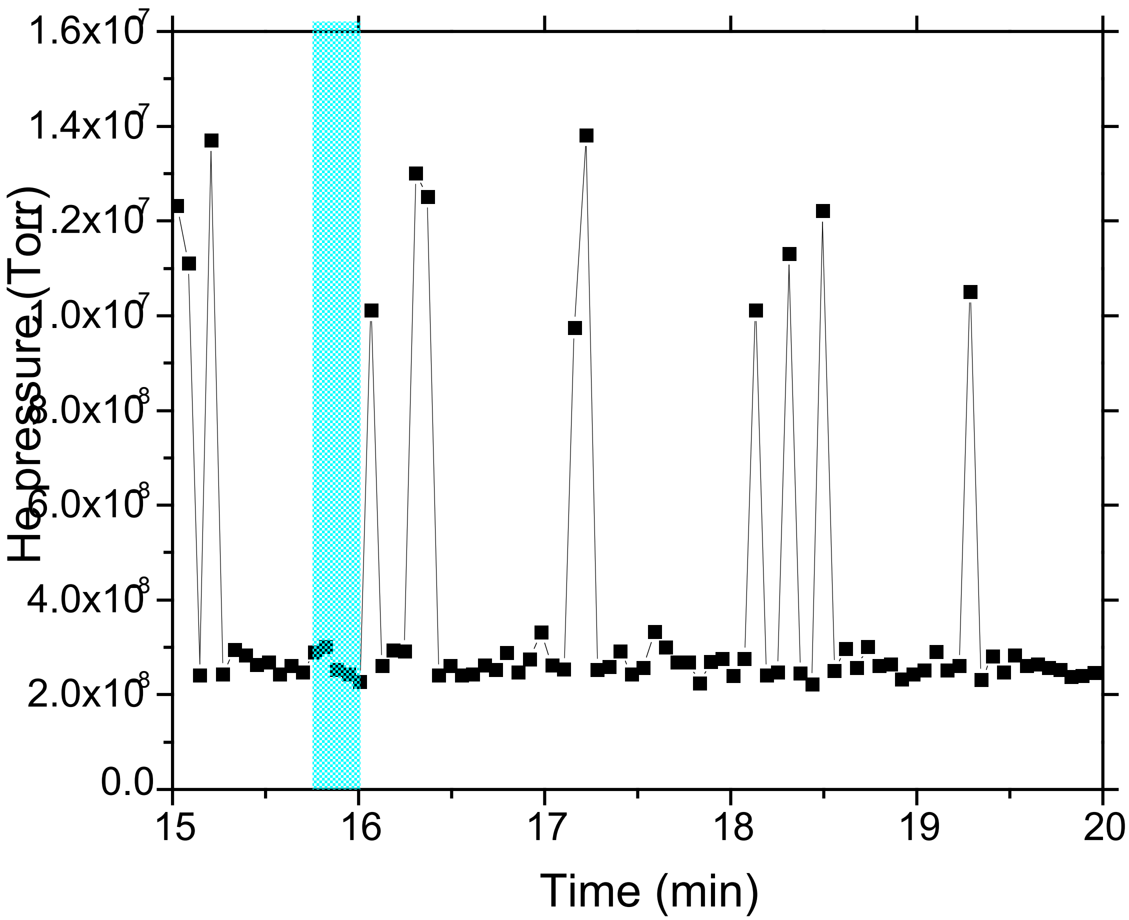
He delayed release experiments

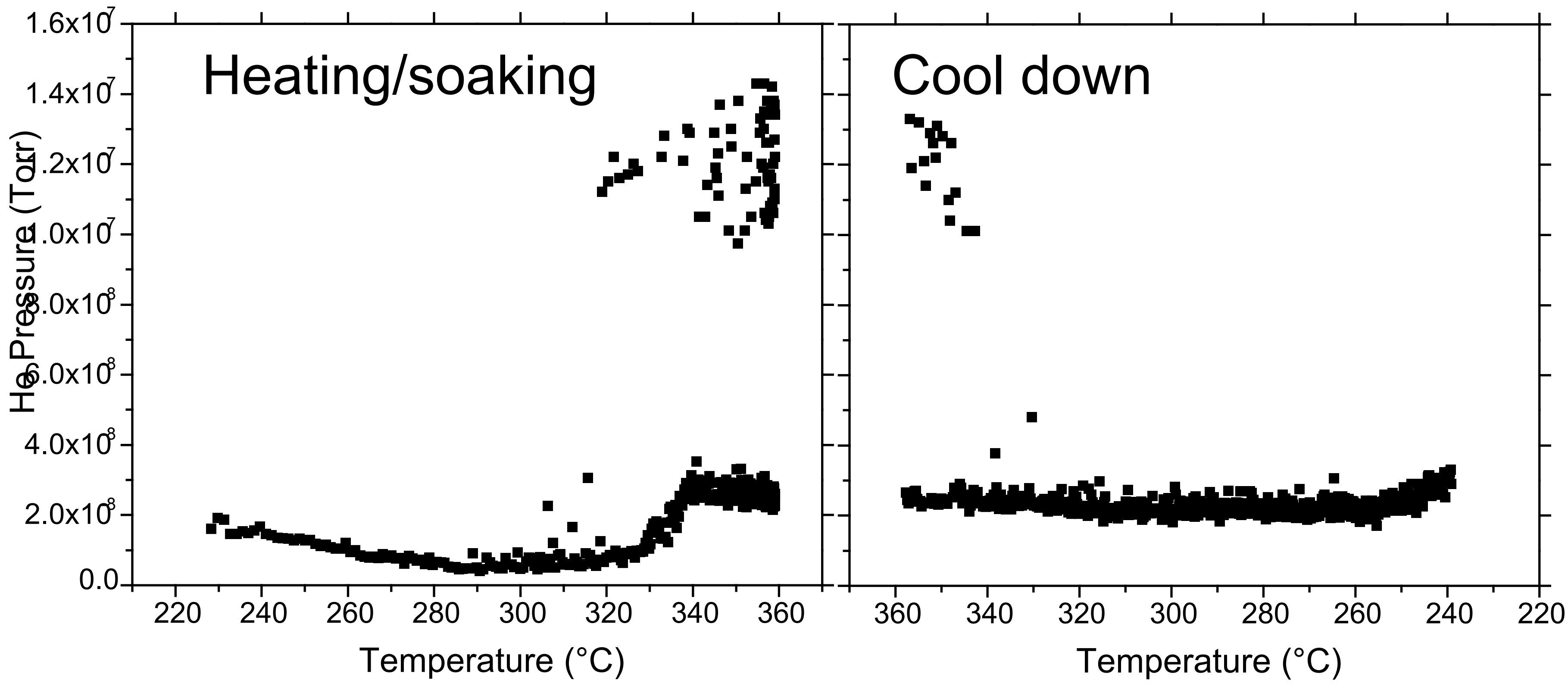
- Lithium flowing on upper chamber with $2x10^{-5}$ Torr He pressure, ion beam NOT on
- The lithium was then heated from 230 to 350 – 355 °C after passing through the upper chamber
- He signal monitored during the heating cycle
- He release rate expected to increase
- Temperature kept for 10 minutes at 350 °C
- Cool down back to 230 °C

He release during Li annealing

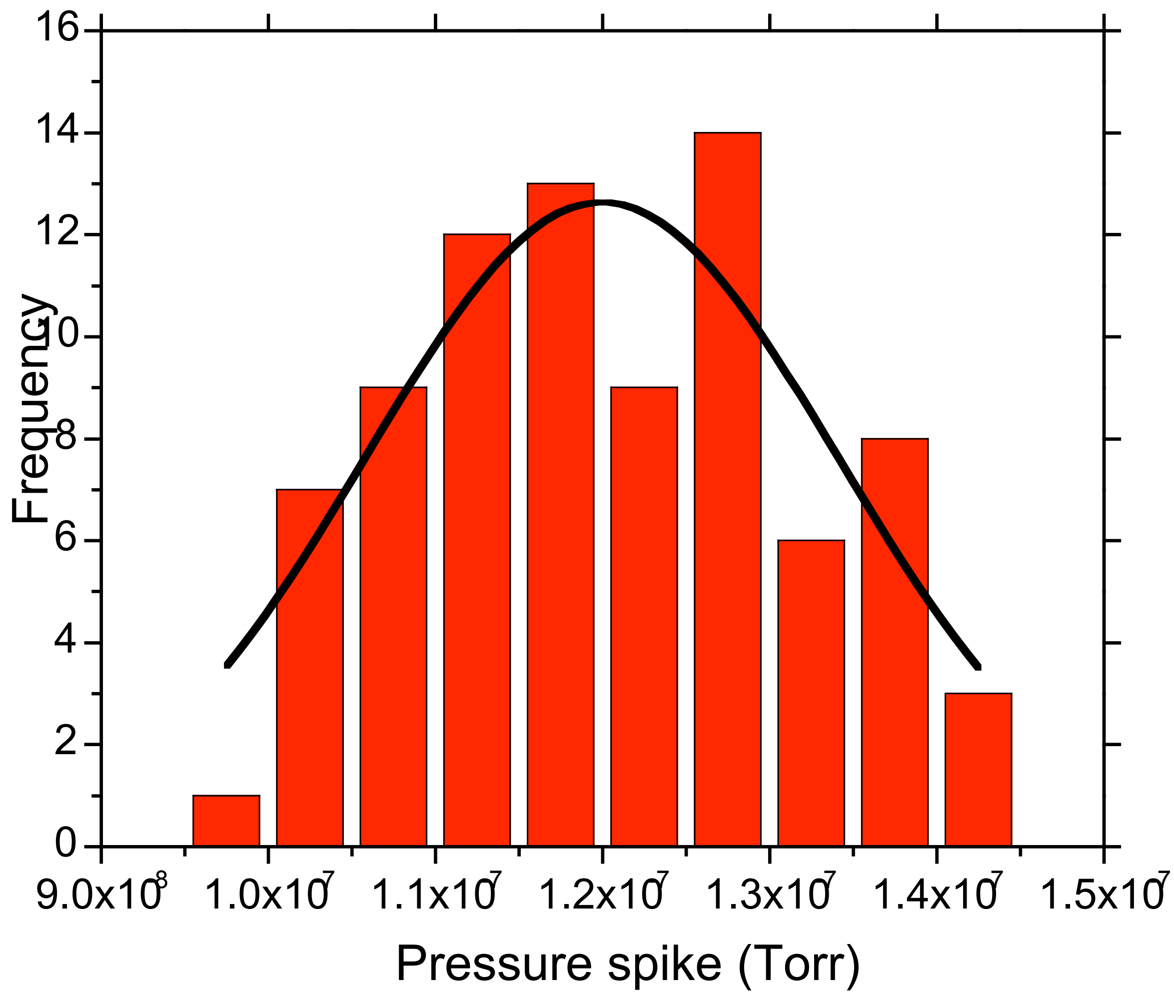


- Series of He spikes appear upon heating
- Temperature threshold for bubble release

Temperature threshold for bubble release



Pressure spike distribution



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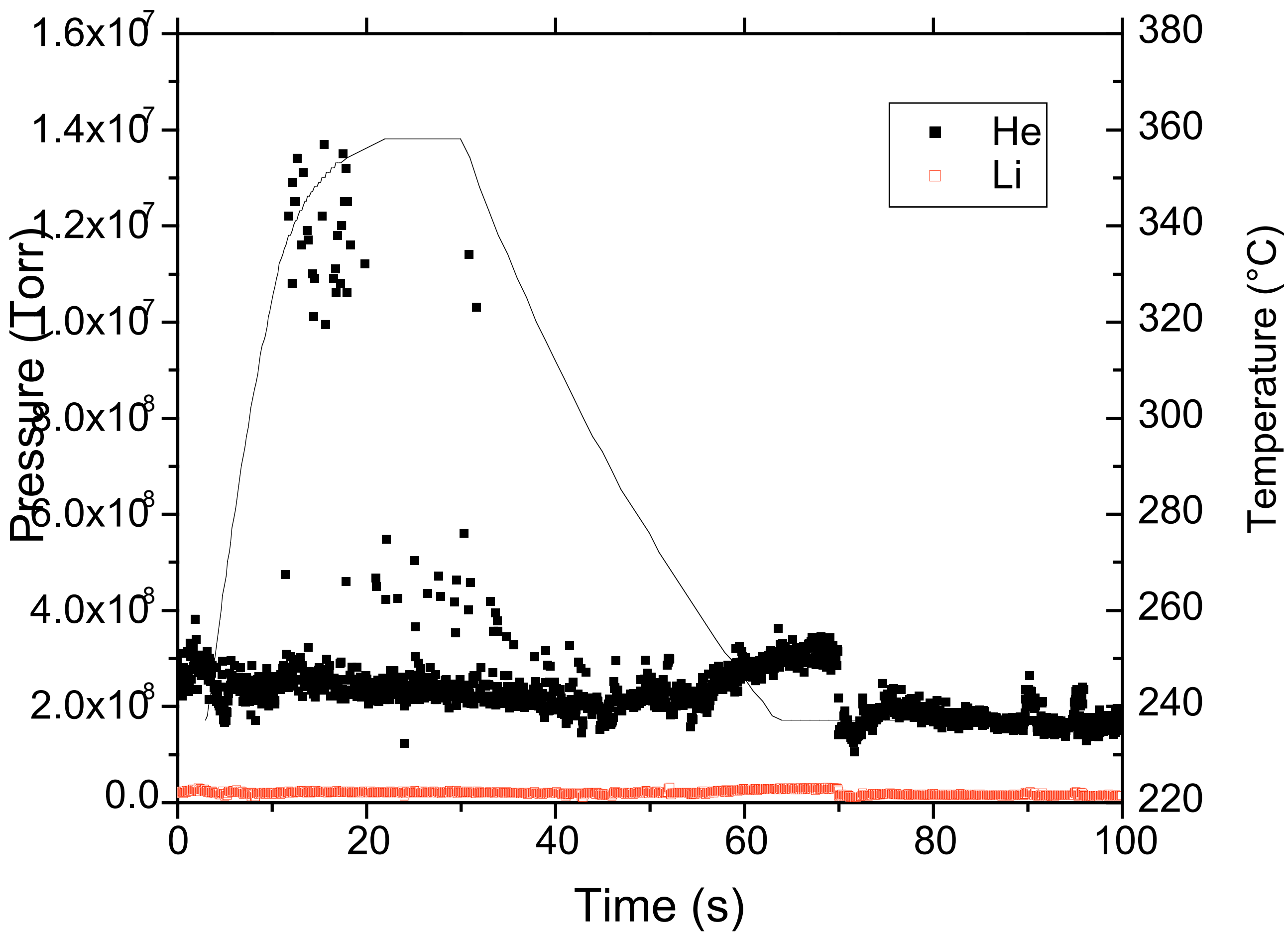
Second annealing

- Experiment identical to the previous one performed
- Verify reproducibility
- Bubbles were observed again
- They get smaller with time
- Indication of He removal?



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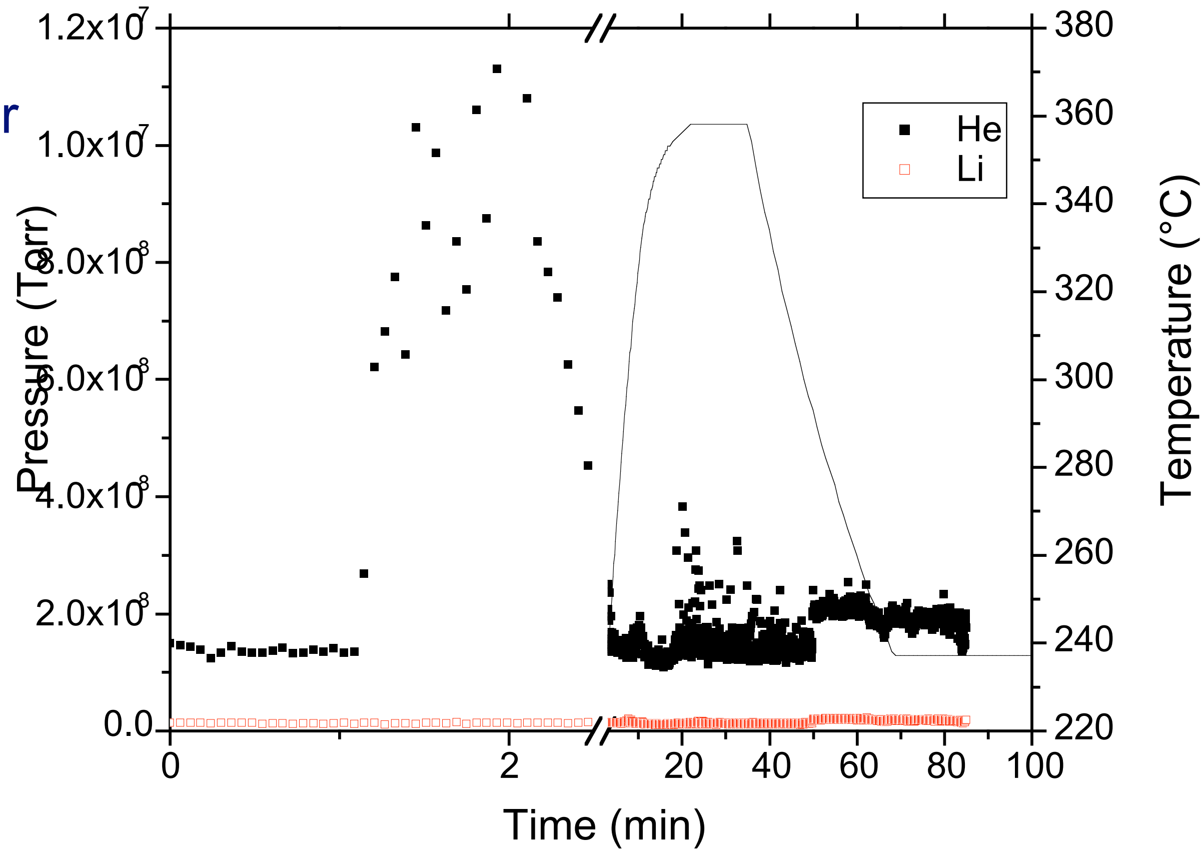
He pressure trace, prompt and long-term release

- 80% comes out before heating starts (prompt)
- Series of He spikes appear upon heating
- Pressure signal integrated with time for prompt and long-term regions
- About 20% of He comes out later
- Was residual He completely removed in the first two annealing experiments?
- More studies necessary



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Helium results (1)

- Retention as a function of energy was measured
- Retention is linear with energy
- Zero retention is observed for zero energy
- Retension is ndependent of ion current
- Square root dependence with velocity
- Follows expected trends

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Helium results (2)

- Model for implanted He transport developed
- Model allows estimate of an effective diffusion coefficient
- $D=(2.3\pm0.4)\times10^{-7}\ \mathrm{cm^2/s}$ @ $T=230\pm10\ ^{\circ}\mathrm{C}$
- This is very promising for using flowing Li for He removal in fusion systems.

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Helium results (3)

- Experiments looking for long-term He trapping were performed
- Apparent He bubble release was observed
  - Calculated diffusion coefficient is orders of magnitude lower than expected – Could bubbles be responsible for this?
- Initial measurements show 20% of the He as trapped long-term

Future work (1)

- The long-term release of helium needs to be studied more in depth
- The model needs to be corrected to account for the fraction retained long-term
- Upgrade to a higher flux plasma source to study another regime and compare with the present one

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Desired ELM Parameters

- Anticipated initial funding route is SBIR through Starfire Industries LLC
- Near-term (Phase I) goal is proof-of-principle ELM simulator demonstrating accurate simulation of ELM parameter for fusion power reactor
- Long-term goal is a flowing liquid PFC ELMs plasma test facility to provide design and scale up data for the PFC community

ELM Parameter	**Value**
Power Loading	~1-3 MJ/m^2
ELM Event Frequency	~1-10 Hz
Total ELM Duration	~0.1-1 msec
Blob Subfrequency	~10-100 kHz
Blob Pulse Width	~5-20 _sec
Plasma Temperature During ELM	~1-2.5 keV
Plasma Density During ELM	~10^{19} m^{-3}
Magnetic Field Strength At Divertor	~1-5 T
Normal Edge-Region Plasma Temperature	~10-100 eV
Normal Edge-Region Plasma Density	~10^{18} m^{-3}

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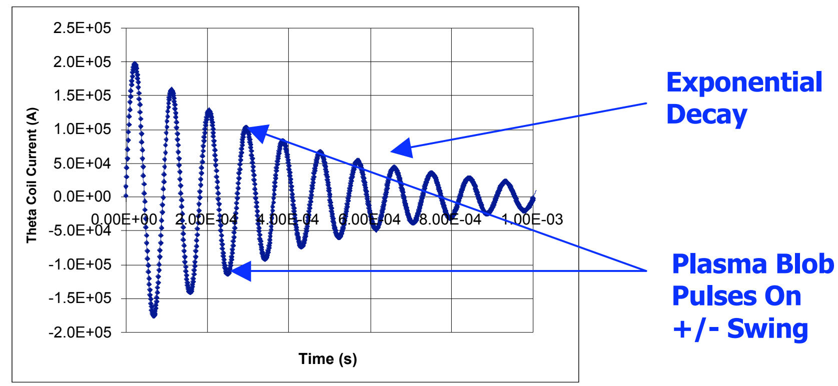
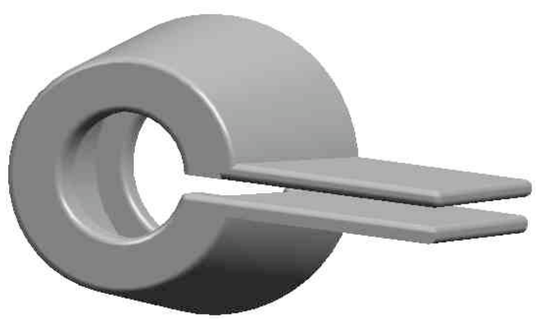
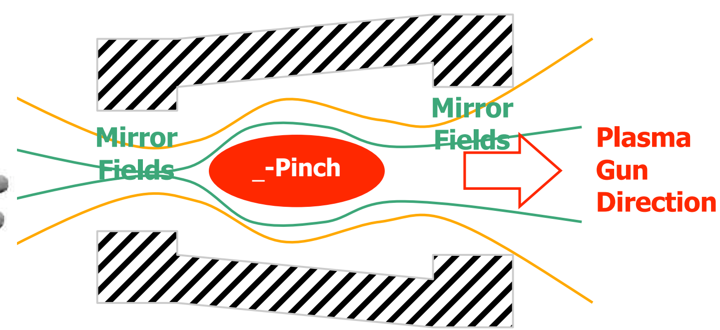
Conical Theta Pinch

- Estimated theta pinch oscillation and plasma generation for a 200_F capacitor bank at 15kV yields a subfrequency of about 100kHz, as desired.
- Mirror ratio of approximately 2-4 to achieve characteristic blob timescale on the order of ~10_sec







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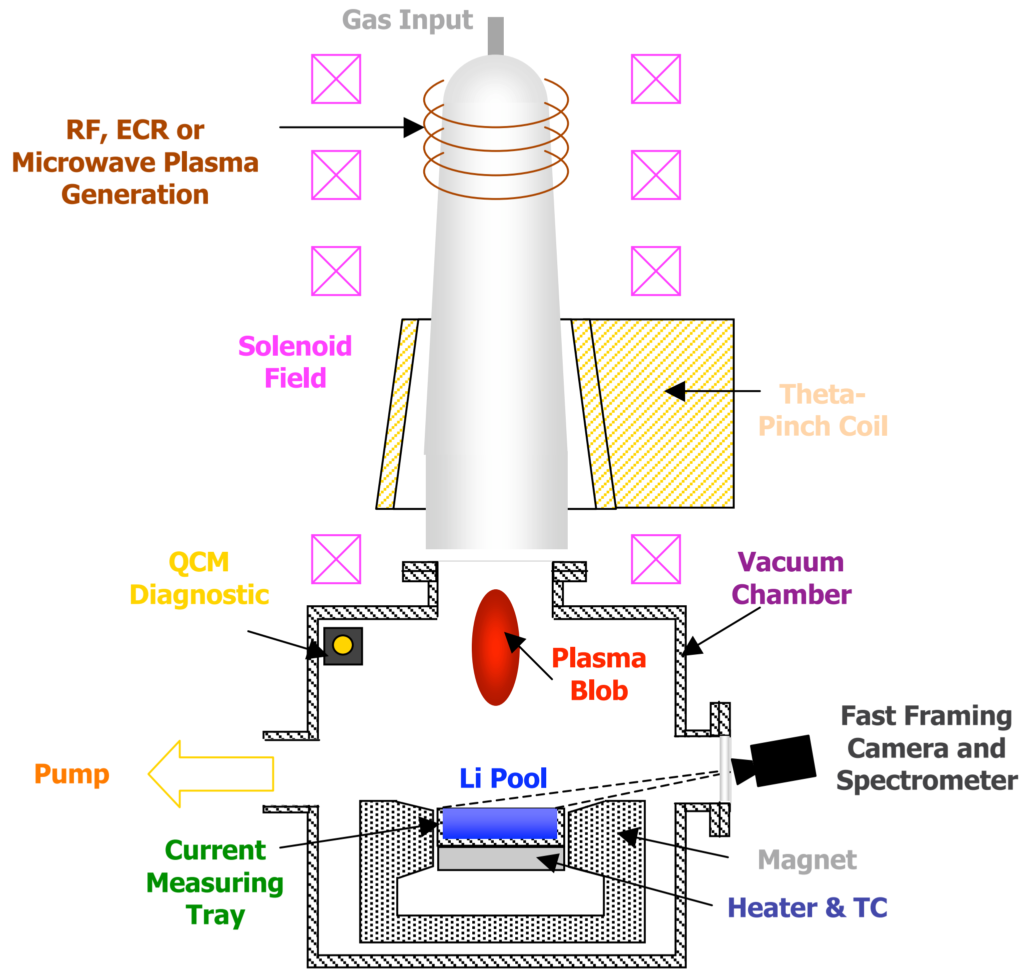
Phase I ELM Simulator at UIUC

- Initial experiments carried out on static pool of lithium
- Erosion measurements of liquid lithium subject to high heat flux plasma
- MHD effects can be examined
- Evaluation of other PFCs is simple modification
- Can extend to flowing Li experiments in Phase II



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